Paleogeographic and paleoclimatic significance of diatoms from middle Pleistocene marine and glaciomarine deposits on Baldwin Peninsula, northwestern Alaska

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Abstract

A newly revised diatom biostratigraphic scheme for the North Pacific Ocean based on studies of the diatom flora of the Cape Blossom and Hotham Inlet Formations of Baldwin Peninsula, northwestern Alaska provides new information on the paleoceanography of Kotzebue Sound, Alaska, during middle Pleistocene time. Sediments exposed along coastal bluffs of Baldwin Peninsula contain subarctic North Pacific zonal-index species, including extinct *Proboscia barboi*, *Pr. curvirostris*, *Actinocyclus ochotensis* var. *fossilis*, *Thalassiosira nidulus* var. *nidulus*, *Th. jouseae*, *Th. gravida* var. *fossilis*, and *Stephanopyxis dimorpha*, which are correlated with the middle part of the *Proboscia barboi* Zone (0.43–0.36 Ma). Based on the distribution of the zonal diatom species and on changes in the paleoecological structure of the diatom assemblages (e.g., warm- vs. cold-water assemblages), we conclude that the marine deposits of the Cape Blossom Formation and lower Baldwin Silt member of the Hotham Inlet Formation formed under relatively warm, high sea-level conditions associated with the marine oxygen isotope stage (OIS) 11 transgression. Glaciomarine sedimentation (middle and upper Baldwin Silt and Selawik Gravel members of the Hotham Inlet Formation) initiated during relatively warm conditions at the end of the stage 11 transgression and continued into stage 10. High-latitude glacier growth during a global 'interglacial' period was likely facilitated by warm surface waters on flooded continental shelves and limited regional sea ice cover. The biostratigraphic record at Baldwin Peninsula provides further evidence that high-latitude ice growth is favored by increased moisture supply during warm climatic intervals and inhibited by arid conditions during full glacial intervals. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Alaska; Baldwin Peninsula; middle Pleistocene; diatoms; biostratigraphy; paleogeography; paleoclimatology

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1. Introduction

The Pleistocene paleoclimate history of the North Pacific region is not as well studied as the North Atlantic; however, the Beringian region (eastern Russia, Siberia, western Alaska and adjacent continental shelves) played a pivotal role as a pathway for both terrestrial floral and faunal migrations (including early humans) as well as a gateway for exchanges of North Pacific and Arctic Ocean waters. During Pleistocene time, the shallow Bering/Chukchi shelves were alternatively submerged and emerged due to eustatic sea-level changes caused by global ice volume fluctuations. As sea level fluctuated, Pleistocene terrestrial-based glaciers advanced onto the Bering/Chukchi shelves from highlands in western Alaska and eastern Russia several times (Kaufman and Brigham-Grette, 1993); however, these local glaciers were not entirely synchronous with larger, lower-latitude ice sheets (e.g., Hopkins, 1972; Huston et al., 1990; Roof, 1995a,b; Kaufman et al., 1996). Although the number and general timing of Beringian glacial advances is well constrained from terrestrial records (e.g., Kaufman et al., 1991; Kaufman and Brigham-Grette, 1993; Hamilton, 1994), a major difficulty has been definitively placing Beringian terrestrial climatic events into global temporal frameworks such as the marine oxygen isotope record or biostratigraphic zonal schemes. On Baldwin Peninsula (BP), located in Kotzebue Sound (KS) (Fig. 1), a complete sequence of marine, glaciomarine, and glacial sediments, previously identified as representing a middle Pleistocene glacial advance from the Brooks Range (Huston et al., 1990), is well exposed along 30–40 km of coastal bluffs. The sedimentology, stratigraphy, and terrestrial paleoecology of these units have been well-studied (Hopkins et al., 1961; McCulloch et al., 1965; Huston et al., 1990; Hamilton, 1994; Roof, 1995a), but until now, the marine microfossils have not been examined. This study was undertaken to constrain the age of BP marine and glaciomarine deposits using diatom biostratigraphy, estimate the sea-level rise during the Anvilian transgression, and test the hypothesis presented by Huston et al. (1990) that the extensive middle Pleistocene glaciation in northwestern Alaska occurred out-of-phase with global glaciation. This paper presents a newly refined diatom biostra-

tigraphic zonal scheme for the North Pacific and Beringian region and reports on the diatom stratigraphy of the BP sediments. The new Plio–Pleistocene diatom zonal scheme places the age of the BP deposits firmly in middle Pleistocene time (middle part of diatom zone *Proboscia barboi* (0.43–0.36 Ma) which correlates to oxygen isotope stages 11–10. Oxygen isotope stage 11 represents one of the very few times during the last 500,000 years when global temperatures were warmer and sea level higher than today (Burckle, 1994). A better understanding of environmental conditions during the stage 11 warm interglacial interval is important because this warm interval may provide the best picture of what we may expect in a future warmer greenhouse world (Howard, 1997).

An additional unique aspect of the Baldwin Peninsula glacial deposits is that biofacies and lithofacies indicate that the initial phases of glacier expansion and glaciomarine sedimentation occurred during the oxygen isotope stage 11 interglacial period, when global sea level was high enough to cover the shallow Bering Shelf. The timing of the middle Pleistocene Baldwin Peninsula advance with respect to high sea level appears consistent with observations by Miller and de Vernal (1992) that Late Pleistocene polar glaciations also occurred near the end of interglacial periods, when global sea level was high, high-latitude oceans were relatively warm, and summer insolation was decreasing. The biostratigraphic and sedimentary record at Baldwin Peninsula provides further evidence that ice growth at high latitudes is facilitated by increased moisture supply during warm climatic intervals and hampered by arid conditions during cold intervals.

2. Geologic setting

Baldwin Peninsula is a push–moraine complex consisting of glacially deformed middle Pleistocene marine, fluvial and glaciogenic sediments formed by glaciers which flowed over 200 km from the western Brooks Range to Kotzebue Sound (KS) via the Noatak, Kobuk and Selawik river valleys (Fig. 1) (Hopkins et al., 1961; McCulloch et al., 1965; Hamilton, 1986, 1994; Huston et al., 1990; Roof, 1995a). BP and KS lie on the Chukchi Shelf,
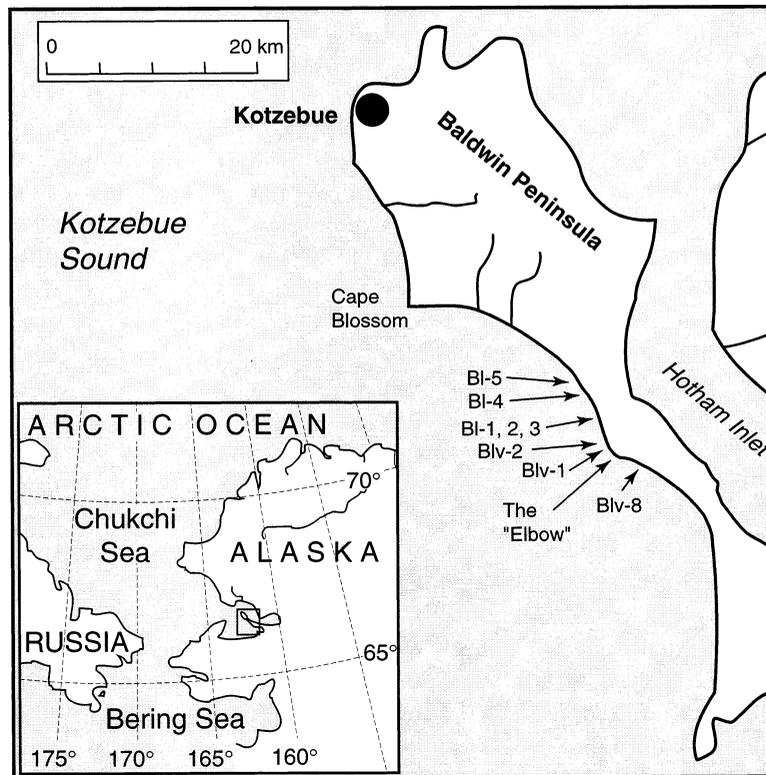
Fig. 1. Map of the Kotzebue Sound region, Alaska and location of study sections mentioned in the text.

within the Selawik Basin, which is a Tertiary intra-continental basin formed by extensional faulting (Decker et al., 1989). The Bering and Chukchi continental shelves have been largely stable throughout late Neogene and Pleistocene time (Decker et al., 1989; Marlow et al., 1994).

2.1. Lithostratigraphy of Baldwin Peninsula

McCulloch et al. (1965) investigated exposures along BP, Hotham Inlet, and Selawik Lake (Fig. 1) and identified the following Quaternary units (from oldest to youngest): marine sediments from the 'Yarmouth' interglacial interval; Illinoian glacial till and associated outwash; late Illinoian loess, thaw lake deposits, and floodplain sediments; Wisconsin loess, and thaw lake sediments; and late Wisconsin to early Recent alluvium. The glacial units were interpreted to be of Illinoian age and the fossiliferous marine and non-marine sediments overlying the drift

were thought to be of Sangamon age (McCulloch et al., 1965).

Throughout the next two decades an effort was made to correlate the numerous high sea-level (transgressive) deposits and glacial deposits found throughout Alaska and eastern Russia (e.g., Hopkins et al., 1965, 1972, 1974; Hopkins et al., 1965, 1967; McCulloch, 1967). In these correlation schemes, the marine sediments of BP (the 'Yarmouth marine sediments' of McCulloch et al., 1965) were renamed the Kotzebuan transgressive deposits and considered middle Pleistocene in age (e.g., Hopkins et al., 1965; Hopkins, 1973). The glacial sediments, which in KS were shown to be much more extensive than younger Wisconsin glacial deposits, were correlated to similarly extensive 'Nome River' glacial deposits mapped on the southwestern Seward Peninsula (Hopkins, 1959; Brigham-Grette and Hopkins, 1989). Subsequent work resulted in definitions of new stratigraphic units and re-interpretations
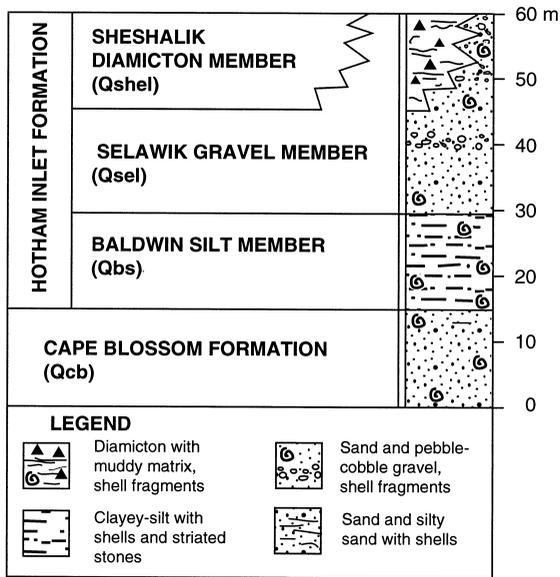
Fig. 2. Current lithostratigraphic names used for the sediments exposed along coastal bluffs of Baldwin Peninsula (from Huston et al., 1990).

of their genesis. Four middle Pleistocene lithologic units along BP are now recognized: the Cape Blossom Formation (Qcb); and the Baldwin Silt (Qbs), Selawik Gravel (Qsel), and Sheshalik Diamicton (Qshel) members of the Hotham Inlet Formation (Fig. 2) (Huston et al., 1990; Roof, 1995a).

Although the glacial origin of BP was recognized by Hershey (1909) at the beginning of the century, the age of the glacial event(s) responsible is still not known with certainty. Huston et al. (1990) presented paleomagnetic data and a limited number of amino acid ratios from the various units at BP which suggested an age of approximately 0.40 to 0.60 Ma. Kaufman et al. (1991) combined K–Ar, Ar–Ar, paleomagnetic, and amino acid age estimates for deposits of the Anvilian transgression and succeeding Nome River glaciation on the Seward Peninsula and concluded that the Nome River glaciation occurred between 0.58 and 0.28 Ma, with an age younger than marine oxygen isotope stage (OIS) 11 (0.410 Ma) preferred. Based on similarity of drift morphology and similar extensive glacier limits, the Nome River glaciation is thought to be equivalent to the glacial events recorded in BP (e.g., Kaufman and Hopkins, 1986).

3. Materials and method of study

Bulk sediment samples were collected from beach bluff exposures along the western coast of Baldwin Peninsula, Alaska (Figs. 1 and 3). For each section, diatoms from 5-g sediment samples were identified (at ×1200) until 250 individual specimens were counted, then percent abundances were calculated. In some cases, the total number of diatoms was less than 250, and all valves per slide were identified and counted. Effort was concentrated on the identification of diatoms which went extinct during Pleistocene time, because these taxa are masked by the more abundant sublitoral species, and their occurrences are low.

Two indices, T_d (diatom paleotemperature values) and H_d (diatom relative paleowater depth values), are used for paleogeographic interpretation of the paleoecological structures of the diatom assemblages. As shown by Jousé (1962), Schrader (1973), Koizumi (1973, 1986, 1992, 1994), Sancetta (1981, 1982a,b), and Barron (1992a, 1995), the thanatocoenosis in the uppermost layer of the bottom sediments is related to the biocoenosis which in turn is dependent on surface water temperatures. Thus the diatom assemblages form paleoclimatic series (paleoclimatic successions or cliseries, according to Krassilov, 1977) which reflect both paleoclimatic and sea-level changes during middle Pleistocene time.

According to Kanaya and Koizumi (1966), T_d is defined as:

$$T_d = 100X_w/(X_w + X_c)$$

where X_w is the frequency of warm-water species, and X_c is that of cold-water species.

Paleotemperature is estimated by correlating the T_d values of the fossil diatom assemblages with the recent thanatocoenoses and surface-water assemblages from North Pacific and Arctic biogeographic regions (Jousé, 1962; Koizumi, 1973, 1985a, 1992, 1994; Sancetta, 1981, 1982a; Sancetta and Silvestri, 1984, 1986; Pushkar et al., 1987; Polyakova, 1989; Barron, 1992a, 1995; Shiga et al., 1994). T_d values of the thanatocoenoses in modern seafloor sediments from KS are about 5–7%.

The species for 'warm'-water and 'cold'-water groups were selected according to Jousé (1962), Kanaya and Koizumi (1966), Donahue (1970),
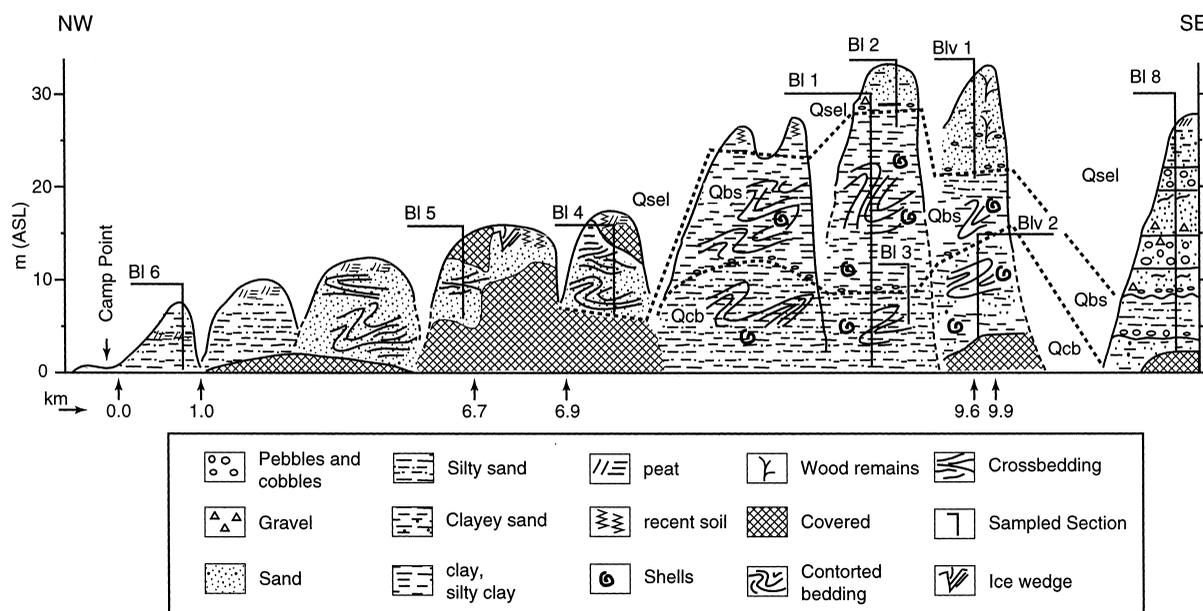
Fig. 3. Schematic diagram of the Middle Pleistocene deposits exposed in beach bluffs along the western shore of Baldwin Peninsula.

Schrader (1973), Koizumi (1973, 1985a, 1986, 1992, 1994), Pushkar (1979), Sancetta (1981, 1982a), Sancetta and Silvestri (1986), and Barron (1992a, 1995).

We include in the relatively 'warm'-water group diatoms of lower and subtropical Pacific latitudes: *Coscinodiscus perforatus* Ehr., *C. radiatus* Ehr., *C. asteromphalus* Ehr. and its varieties *C. asteromphalus* var. *centralis* Grun. and *C. asteromphalus* var. *subbuliens* A. Cl., *Thalassiosira pacifica* Gran et Angst, *Th. oestrupii* (Ost.) Proshk.-Lavrenko, *Actinocyclus divisus* (Grun.) Hust., *A. curvatulus* Janish, *Actinoptychus senarius* Ehr., *Thalassionema nitzschioides* Grun., and *Actinocyclus octonarius* Ehr. We include *Actinocyclus curvatulus* and *A. divisus* which have moderately cold ecological habitats in this group because:

– they are not found in high concentration in the surface waters of the Bering Sea (Jousé, 1962; Sancetta, 1982a);

– these species are dominant in interglacial deposits of the North Pacific (Jousé, 1962, 1969; Sancetta, 1981; Pushkar et al., 1987);

– the warmer-water diatoms are rare, therefore we are compelled to include these moderate diatoms in our temperate group.

The cold-water group includes the arctic and arcto-boreal diatoms *Porosira glacialis* (Grun.) Jorg., *Trigonium arcticum* (Bright.) Cl., *Thalassiosira gravida* Cl., *Th. gravida* var. *fossilis* Jousé, *Th. kryophila* (Grun.) Jorg., *Th. hyalina* (Grun.) Gran, *Th. nordenskioeldii* Cl., *Bacterosira fragilis* Gran, *Nitzschia grunowii* (Cl.) Hasle, *Navicula directa* W. Sm., *Melosira arctica* (Ehr.) Dickie, and *Paralia sulcata* (Ehr.) Cl.

As shown by Jousé (1962), Koizumi (1973, 1994), Pushkar (1979), and Sancetta and Silvestri (1984, 1986), these species are abundant in sediments of the North Pacific correlating to Pleistocene glacial periods. However, we have to consider carefully the high occurrence of some sublittoral species (e.g., *Paralia sulcata*) because their temperature affinity may change under conditions of low salinity (Jousé, 1962; Tanimura, 1981; Sancetta, 1982a).

In this paper the north-boreal (Jousé, 1962) diatoms are equivalent to the subarctic diatoms of Sancetta (1981, 1982a) and Sancetta and Silvestri (1986), and south-boreal diatoms are equivalent to their moderately warm transition group diatoms.

H_d is a paleogeographic index (Pushkar and Cherepanova, 1996; Yanagisawa, 1996 — as indices Bd1 and Bd2) which is defined as:

$$H_d = 100X_p/(X_p + X_b)$$

where X_p is the frequency of planktonic species and X_b is that of benthic.

Increasing H_d values indicate increasing relative water depth. The index is based on the fact that diatom communities reflect the optimal ecological depth of their growth and productivity (e.g., Jousé, 1962; Round, 1970; Sancetta, 1982b; Yanagisawa, 1996). This factor is a useful indicator of bathymetry, not only in the recent Bering Sea (Sancetta, 1982b; Yanagisawa, 1996), but also in the Middle Miocene Taga Group of Japan (Yanagisawa, 1996), and Pliocene to Pleistocene marine sequences in the Okhotsk Sea (Jousé, 1962; Shiga et al., 1994; Pushkar and Cherepanova, 1996). The species for planktonic and benthic groups were selected according to Jousé (1962), Hendey (1964), Round (1970), Koizumi (1973), Schrader (1973), Pushkar (1979), Sancetta (1981, 1982a,b) and Yanagisawa (1996). The planktonic group is represented by *Thalassiosira gravida* var. *gravida* Cl., *Th. gavida* var. *fossilis* Jousé, *Th. eccentrica* (Ehr.) Cl., *Bacterosira fragilis* Gran, *Coscinodiscus marginatus* var. *marginatus* Ehr., *C. oculus-iridis* Ehr., *Rhizosolenia hebetata* var. *hiemalis* (Bailey) Cl., *Porosira glacialis* (Grun.) Jorg., *Actinocyclus curvatulus* Jan., *Coscinodiscus radiatus* Ehr., *C. asteromphalus* Ehr. The more abundant benthic sublittoral species are represented by *Trachyneis aspera* Cl., *Diploneis smithii* (Breb.) Cl., *D. interrupta* Cl., *Actinocyclus octonarius* Ehr., and *Paralia sulcata* (Ehr.) Cl.

The N values (Jousé, 1962; Pushkar, 1979; Shiga et al., 1994) show the number of the diatom valves in 1 g of dried sediment. According to Jousé (1962), low numbers of diatoms in some case reflect glacial conditions, because terrigenous sedimentation rates are very high during marine regressions. In addition, diatom productivity during glacial periods in the North Pacific was much reduced (Jousé, 1962). High concentrations of diatoms and greater species diversity reflect moderately warm periods. These statements hold as long as the marine sediments were not changed by diagenetic processes or diatom dissolution (Jousé, 1969; Burckle et al., 1992). But we must remember that the concentration of diatom valves may also be high in shallow water marine and periglacial lakes during spring and summer,

when water temperatures are warm enough for diatom growth and reproduction (Proshkina-Lavrenko, 1974).

The diatom assemblages of the BP middle Pleistocene sediments are represented on the whole by well preserved valves throughout the sections, without any traces of dissolution. The Cape Blossom Formation (Qcb) contains rich diatom assemblages, while in general diatoms are rare in the Baldwin Silt member (Qbs). Traces of redeposited diatom valves are found in the upper part of Qcb deposits and more clearly in Qbs deposits. Such species as *Coscinodiscus marginatus* var. *fossilis* Jousé, *C. pustulatus* Mann, *Stephanopyxis schenckii* Kanaya, *Thalassiosira zabelinae* Jousé, and *Actinocycylus ingens* Rattray were reworked from surrounding Chukchi Sea Miocene and Pliocene deposits, in which these species are dominant (Ivanov, 1986; Polyakova, 1991). These redeposited poorer preserved valves are found with rare occurrence (1–5 valves per slide). The index-species *Proboscia barboi* (Brun.) Jordan et Priddle, *Pr. curvirostris* (Jousé) Jordan et Priddle, and *Actinocyclus ochotensis* var. *fossilis* Pushk. found are likely in situ, because they are rare in Pliocene Arctic deposits and it is unlikely that these species (with good preservation) were redeposited with the same frequency as of the Neogene species named above.

The proposed Plio–Pleistocene diatom zonal scheme (Pushkar, 1985; Pushkar and Cherepanova, 1995, 1996; Cherepanova et al., 1997) is based on the classic standard subarctic zones of Koizumi (1973, 1985b) and Koizumi and Tanimura (1985), with important additions to the zonal boundary definitions by Akiba (1986), Sancetta and Silvestri (1986), Pushkar et al. (1991), Gladenkov (1994), and Barron and Gladenkov (1995). We use our newly modified and more detailed diatom zonal scheme to determine ages of the diatom assemblages from the Pleistocene deposits of BP, and their biostratigraphic position (Fig. 4). The zonal boundaries in this proposed scheme have been recognized and defined by levels of extinction or evolutionary first appearance of stratigraphically useful diatom species. The Pleistocene diatom datum levels for the Late Pliocene to Pleistocene zonal scheme were selected according to Schrader (1973), Koizumi (1985b, 1986, 1992, 1994), Koizumi and Tanimura (1985), Pushkar (1985), Pushkar et

Plio-Pleistocene North Pacific Diatom Zonal Scheme

Epoch	Magneto-strat.	Diatom Zone	Evolutionary Events (↑ First Appearance; ↓ Last Appearance)
PLEISTOCENE (Upper)	Brunhes	Neodenticula seminae (0.075) 0.095 Ma	*Proboscia curvirostris*
		Proboscia curvirostris 0.13 Ma	↓ *Thalassiosira gravida* var. *fossilis*
PLEISTOCENE (Middle)	Brunhes	Thalassiosira gravida var. fossilis (0.19) 0.2 Ma	↓ *Thalassiosira nidulus* var. *nidulus* / *Pyxidicula dimorpha*
		Thalassiosira nidulus var. nidulus (0.22) 0.23 Ma	↓↓ ↑ *Actinocyclus ochotensis* (common)
		Actinocyclus ochotensis var. fossilis 0.28 Ma	↓↓ *Actinocyclus ochotensis* var. *fossilis* / *Thalassiosira jouseae* / *Proboscia barboi*
		Proboscia barboi (0.52) 0.63 Ma	↓ *Nitzschia reinholdii*
		Nitzschia reinholdii 0.65 Ma / 0.79 Ma	↓ *Nitzschia fossilis* (common)
PLEISTOCENE (Lower)	Matuyama	Nitzschia fossilis 0.88 Ma (0.92) 0.94 Ma	↓↓ *Mesocena elliptica* (Silicoflagellate) / *Actinocyclus oculatus* / *Coscinodiscus marginatus* var. *fossilis* / *Rhizosolenia matuyamai Neodenticula koizumii*
		Actinocyclus oculatus 0.97 Ma (1.66) 1.7 Ma	↑↓↓↓↓ *Rhizosolenia matuyamai* / *Thalassiosira antiqua* / *Stephanopyxis horridus*
PLIOCENE (Upper)	Matuyama	Thalassiosira antiqua 1.88 Ma	↓↓ ↑↑ *Stephanopyxis dimorpha Proboscia curvirostris*
		Pyxidicula zabelinae 2.2 (2.3) Ma	↓↓ *Pyxidicula zabelinae* / *Coscinodiscus pustulatus* / *Thalassiosira convexa*
		Thalassiosira convexa (2.5) 2.58 Ma	↓ ↑ *Stephanopyxis horridus*
PLIOCENE (Upper)	Gauss	Neodenticula koizumii 3.1 Ma	↓↓ ↓↓ *Neodenticula kamtschatica* / *Koizumia tatsunokuchinensis* / *Thalassiosira jacksonii* / *Thalassiosira nativa*
PLIOCENE (Lower)	Gauss	Neodenticula kamtschatica 3.4 Ma / 3.7 Ma	↑↑ *Actinocyclus oculatus* / *Actinocyclus ochotensis sensu lato* / ↑ *Neodenticula koizumii*

Fig. 4. Plio–Pleistocene North Pacific Zonal Scheme (Pushkar and Cherepanova, 1995). Ages shown in parentheses represent zonal boundaries at higher latitudes.

al. (1991), Barron (1992b), Gladenkov (1994) and Barron and Gladenkov (1995). The diatom assemblages of this zonal scheme are partially known in Arctic and North Pacific regions (Jousé, 1962, 1969; Sheshukova-Poretskaya, 1967; Koizumi, 1973, 1985a,b, 1986, 1992; Dolmatova and Nevretdinova, 1975; Oreshkina, 1980, 1985, 1993; Pushkar, 1983, 1985; Pushkar et al., 1987, 1991, 1997; Laukhin et al., 1989; Polyakova, 1989, 1991; Losseva, 1992; Barron, 1992a, 1995; Basilyan et al., 1993; Gladenkov, 1994; Barron and Gladenkov, 1995; Pushkar and Cherepanova, 1996). The zonal boundaries have been dated by more than 150 ^{230}Th/^{234}U, ^{234}U/^{238}U and thermoluminescence dates, and are correlated with magnetostratigraphic and oxygen isotopic data (Pushkar et al., 1987; Pushkar and Cherepanova, 1996; Cherepanova et al., 1997).

Following Berggren et al. (1985), we place the lower/middle Pleistocene boundary at the Brunhes–Matuyama boundary, and the beginning of the Late Pleistocene at the beginning of oxygen isotopic substage (OIS) 5e (Williams et al., 1988; Shackleton et al., 1990).

Because diatom provincialism is largely related to the distinct latitudinal zonality of surface-water masses (Koizumi, 1973), critical examination of the paleoecological history, including the rate of population expansion after the species appearance and the rate of population degradation during extinction time, is necessary for the evaluation of biostratigraphic levels. We argue that most subarctic diatom species populations with unique ecological features expanded from the Kurile Island upwelling region toward the Arctic Basin and moderate latitudes of the Japan Sea and open Pacific. Thus, the levels of their first appearances are earlier in the Kurile region than in the Subtropic and Arctic regions (Pushkar et al., 1998a,b). The last appearances or extinctions of subarctic diatoms are probably earlier in the middle-latitude regions than in the high-latitude Bering and Chukchi Seas (Pushkar, 1985; Koizumi, 1985a,b, 1992, 1994; Pushkar et al., 1991; Gladenkov, 1994; Barron and Gladenkov, 1995). As shown in Fig. 4, some zonal boundaries are asynchronous between middle (open data) and high (data in the brackets) latitudes.

The taxonomy of the diatoms used follows that of Koizumi (1973, 1985a, 1992, 1994), Sancetta

(1982a), Koizumi and Tanimura (1985); Makarova (1988), Takahashi et al. (1994) and Yanagisawa (1994).

4. Section descriptions

4.1. Cape Blossom Formation (Qcb)

4.1.1. Lithology

The lowest exposed unit of BP, the Cape Blossom Formation (Qcb) consists of massive to laminated clay and silt interbedded with massive to cross-bedded micaceous silty sand beds with stratigraphic thickness up to 15 m, although the lower contact is not exposed. Cross-bedding is typically weakly asymmetric, indicating lateral migration of oscillation ripples, but in a few beds, climbing ripples indicate rapid sediment accumulation under unidirectional currents. The entire Qcb shows a coarsening-upwards trend with sand-rich lithofacies dominating the upper 5 m. The upper 1–2 m of the Qcb is characteristically well-sorted medium-fine sand with parallel and ripple laminations and very fine wood or plant fibers concentrated in thin lenses draped over ripple-bedded sand.

Additional structures in the Qcb include postdepositional deformation such as dish structures, folded and truncated beds, and small offsets and drag folds along short but distinct faults. These structures are taken to indicate dewatering of rapidly deposited sediment, soft sediment slumping, and plowing by sea ice, but some may have been generated during subsequent glaciotectonic deformation.

4.1.2. Fauna

Macrofossils are rare, but are found scattered throughout all the lithologies of the Qcb. Most fossils found are single mollusc valves showing evidence of redeposition, but some paired valves were found in growth position. The molluscan genera *Astarte* and *Macoma* are most common, but *Cyrtodaria* and *Portlandia* are also present. Gastropods recovered include *Natica*, *Cylichna*, *Plicifusus*. As noted by Hopkins (1972), the fauna contain no extinct species and are similar to modern high arctic fauna characteristic of shallow (10–20 m) nearshore marine conditions.

Ostracodes recovered include *Heterocyprideis sorbyana*, *Rabilimis septentrionalis*, and *Cytheretta teshekpukenis*. These species are common in the modern Beaufort Sea and are characteristic of shallow (<20 m) nearshore marine environments which experience seasonal sea ice and seasonal temperature and salinity fluctuations (E. Brouwers, written commun., 1993).

4.2. Baldwin Silt member of the Hotham Inlet Formation (Qbs)

4.2.1. Lithology

The lower Qbs is invariably massive to faintly laminated blue-gray clayey-silt with a blocky appearance and occasional fine laminations of silt and fine sand. The Qbs is the most commonly exposed middle Pleistocene unit, often deformed and forming vertical cliffs up to 60 m high. Small pebbles up to 5 cm diameter are found scattered throughout the Qbs. In the uppermost Qbs, near the gradational boundary with the overlying Qsel, beds of rippled sand and clast-supported gravel 10–50 cm thick commonly become interbedded with the clayey-silt lithology.

4.2.2. Fauna

Bivalve shells are dispersed throughout this unit, but shells are more generally abundant in the lowest 2 m. Most shells are poorly preserved single valves, although paired valves filled with clean fine sand were also encountered. *Astarte* is the most common bivalve found in the Qbs; *Macoma*, *Portlandia*, and *Cyrtodaria* are present, but rare.

Ostracode taxa recovered are similar to those found in the Qcb and are indicative of a nearshore inner shelf marine environment, though perhaps slightly more estuarine than indicated for the Qcb (E. Brouwers, written commun., 1993).

4.3. Selawik Gravel member of the Hotham Inlet Formation (Qsel)

4.3.1. Lithology

Overlying the massive clayey-silt of the Qbs are cross-bedded sand and massive-to-graded gravel and cobble beds of the Qsel of the Hotham Inlet Fm. The lower beds of Qsel typically are laterally continuous coarse sand with fine sandy laminations and occa-sional clay drapes and flasers. The upper Qsel consists primarily of normally graded coarse sand and clast-supported gravel and cobbles in beds 20–200 cm thick. Asymmetric ripples and climbing ripples are common in sand beds and lenses. Pebble-rich diamictons up to 1 m thick are randomly distributed in the upper Qsel.

4.3.2. Fauna

Marine mollusc fragments are scattered throughout the Qsel, but all are severely fractured and abraded. Rounded fragments of *Astarte* hinges (the thickest part of the shell) were most commonly observed.

5. Diatom assemblages and zonal stratigraphy

Section Bl 1 is located north of the prominent bend in the west coast of the Peninsula (the 'Elbow', Figs. 1 and 3). Two diatom assemblages are defined from this section (Fig. 5).

Assemblage I was defined in the upper Qcb (stratigraphic interval 0.7–8.5 m above sea level — masl). Diatoms, excluding *Paralia sulcata*, are not abundant, but are well preserved. *Proboscia barboi*, *Pr. curvirostris*, *Thalassiosira gravida* var. *fossilis*, *Th. nidulus* var. *nidulus*, *Th. jouseae*, and *Actinocyclus ochotensis* var. *fossilis* are present. The paleoecological structure of this diatom assemblage consists of planktonic (20–50%) and benthic (80–50%) groups represented primarily by arcto- to north-boreal species (Fig. 5). The large abundance of sublittoral north-boreal *Paralia sulcata* (more than 60%) indicates a lowering of salinity rather than decreasing temperatures. In addition, the presence of moderate and even subtropical species *Coscinodiscus radiatus*, *C. asteromphalus*, and *Thalassiosira oestrupii* are another highly significant element of the paleoecostructure. These diatoms are more abundant in the southern subarctic and transition zones of the Pacific and are not found today above 50ºN latitude (Jousé, 1962; Proshkina-Lavrenko, 1974; ; Koizumi, 1985a, 1992, 1994; Sancetta and Silvestri, 1986; Barron, 1992a). The freshwater diatoms of the genera *Pinnularia*, *Aulacoseira*, *Navicula*, and *Eunotia* are present in the ecological structure of the Qcb assemblage, reflecting possible river runoff.
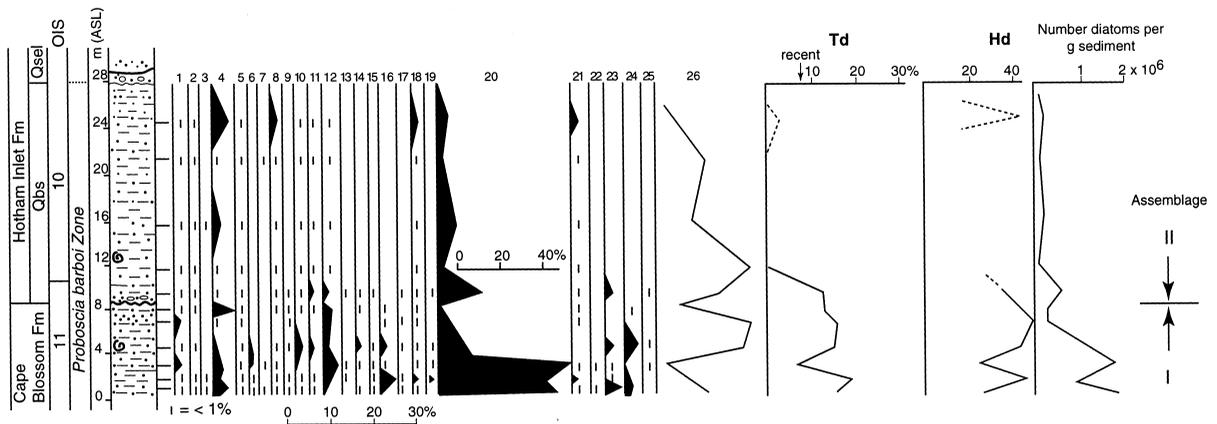
Fig. 5. Diatom diagram of section Bl 1. 1–6 = extinct zonal species: 1 = *Actinocyclus ochotensis* var. *fossilis* Pushk.; 2 = *Proboscia curvirostris* (Jousé) Jordan et Priddle; 3 = *Pr. barboi* (Brun.) Jordan et Priddle; 4 = *Thalassiosira gravida* var. *fossilis* Jousé; 5 = *Th. nidulus* var. *nidulus* Jousé; 6 = *Th. jouseae* Akiba. 7–13 = oceanic and neritic cold-water species: 7 = *Actinocyclus ochotensis* var. *ochotensis* Jousé; 8 = *Bacterosira fragilis* Gran; 9 = *Coscinodiscus marginatus* var. *marginatus* Ehr.; 10 = *Rhizosolenia hebetata* var. *hiemalis* (Bailey) Gran; 11 = *Thalassiosira gravida* var. *gravida* Cl.; 12 = *Th. eccentrica* (Ehr.) Cl.; 13 = *Porosira glacialis* (Grun.) Jorg. 14–17 = oceanic and neritic moderate- and warm-water species: 14 = *Actinocyclus curvatulus* Jan.; 15 = *Coscinodiscus radiatus* Ehr.; 16 = *C. asteromphalus* Ehr.; 17 = *Thalassiosira oestrupii* (Ostenf.) Proshk.- Lavrenko. 18–21 = sublittoral cold-water species: 18 = *Trachyheis aspera* Cl.; 19 = *Diploneis interrupta* Cl.; 20 = *Paralia sulcata* (Ehr.) Cl.; 21 = *Diploneis smithii* (Breb.) Cl. 22–25 = sublittoral moderate- and warm-water species: 22 = *Actinocyclus octonarius* Ehr.; 23 = *Cyclotella striata* (Kuetz.) Grun.; 24 = *Navicula marina* Ralfs; 25 = *N. protracta* Grun. 26 = freshwater diatoms.

Assemblage II was defined in the middle to upper part of the section (8.5–28.0 masl) consisting primarily of the Qbs. In the lowermost part (8.5–9.0 masl), the diatom association is similar to assemblage I, but planktonic species occur less frequently (Fig. 5). The poorer assemblage of the middle and upper parts of the Qbs is dominated by cold-water *Paralia sulcata* and *Thalassiosira gravida* var. *fossilis*. No warm-water diatoms were found. The extinct species are the same as in assemblage I, but also are not abundant.

These two diatom assemblages correlate with the middle of the *Proboscia barboi* Zone according to the proposed diatom scheme (Pushkar and Cherepanova, 1995, 1996; Cherepanova et al., 1997). The paleoecological structures of diatom assemblages I and II allow us to determine their age and to correlate the 'warm' assemblage I with OIS 11 (approximately 0.430–0.380 Ma), while the colder, 'arctic' assemblage II of the middle to upper Qbs corresponds to OIS 10 (0.380–0.360 Ma). The presence of some subtropical species in assemblage I may be explained by the influence of one of the warmest interglacial periods (OIS 11) of the middle Pleistocene.

Section Bl 2 is situated 100 m southeastward of section BI 1 (Fig. 3). In the uppermost part of the Qbs, assemblage I was defined by a poor diatom assemblage characterised by a low diversity and low frequency of taxa, which contains marine cold-water species with 1–2% abundance (Fig. 6): *Actinocyclus ochotensis* var. *fossilis*, *Porosira glacialis*, *Thalassiosira jouseae*, *Th. kryophila*, *Th. hyalina*, *Th. nordenskioeldii*, *Th. nidulus* var. *nidulus*, *Th. gravida et* var. *fossilis*, *Paralia sulcata*, *Bacterosira fragilis*, and *Coscinodiscus marginatus*. Warm elements are absent in this unit. This assemblage is similar to assemblage II from Qbs deposits in section Bl 1.

The sediments of the overlying Qsel contain five diatom assemblages described below.

Assemblage II was found in an organic-rich silt layer (27.8 masl) and is represented by very abundant arcto-boreal *Pinnularia borealis* (20%) and less abundant *Hantzschia amphioxis* var. *capitata* (8.4%). Continental biotopes with sporadic moisture are the typical ecological optimum for these aerophilic diatoms. The marine diatoms of this assemblage are also found with the brackish/estuaric to sublittoral diatom *Navicula protracta* (3.2%).

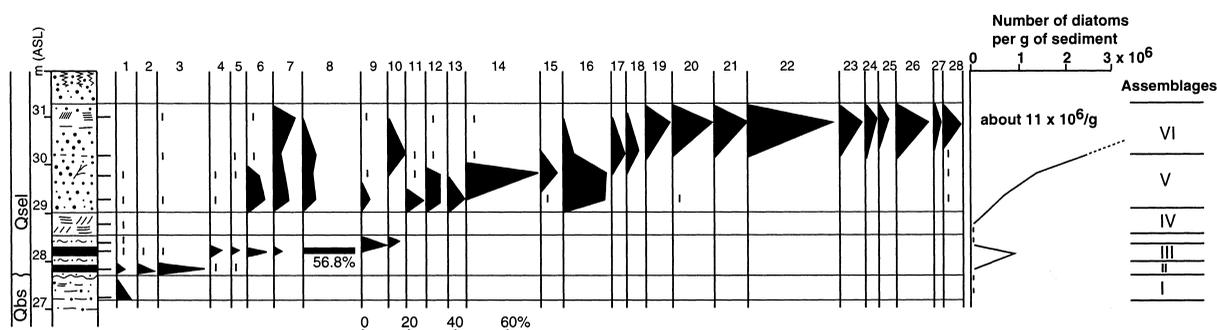Assemblage III was described from an upper interlayer of organic-rich silt (28.35 masl). The

Fig. 6. Diatom diagram of the section Bl 2. 1 = marine diatoms. 2–28 = freshwater diatoms: 2 = *Hantzschia amphioxys* var. *capitata* O.Müller; 3 = *Pinnularia borealis* Ehr., 4 = *Navicula amphibola* Cl.; 5 = *Pinnularia lata* (Breb.) W. Sm.; 6 = *Pinnularia viridis* (Nitzsch.) Ehr. var. *viridis,* var. *intermedia* Cl., var. *sudetica* (Hilse) Cl.; 7 = *Eunotia praerupta* var. *praerupta* Ehr., var. *bidens* (W. Sm.) Grun., var. *muscicola* Boye; 8 = *Fragilaria virescens* Ralfs; 9 = *Tabellaria fenestrata* (Lyngb.) Kuetz.; 10 = *T. flocculosa* (Roth.) Kuetz.; 11 = *Ellerbeckia arenaria* var. *teres* (Brun.) Grawford; 12 = *Eunotia monodon* Ehr.; 13 = *Fragilaria construens* var. *binodis* (Ehr.) Grun., var. *venter* (Ehr.) Grun.; 14 = *Pinnularia hemiptera* (Kuetz.) CI.; 15 = *P. major* (Kuetz.) Cl.; 16 = *Aulacoseira distans* (Ehr.) Sim.; 17 = *Fragilaria constricta* Ehr.; 18 = *Eunotia fallax* A. Cl.; 19 = *Cymbella gracilis* (Rabenh.) Cl.; 20 = *C. naviculiformis* Andrews; 21 = *C. perpusilla* A. Cl.; 22 = *Eunotia triodon* Ehr.; 23 = *E. valida* Hust.; 24 = *Frustulia rhomboides* (Ehr.) D.T.; 25 = *Achnanthes linearis* (W.Sm.) Grun.; 26 = *Navicula bacillum* var. *minor* V.H.; 27 = *Pinnularia legumen* Ehr.; 28 = *Cymbella cuspidata* Kuetz.

freshwater assemblages were dominated by planktonic temperate *Fragilaria virescens* and its varieties (56.8%), while cool-water *Navicula amphibola*, *Pinnularia lata*, *P. viridis*, and its varieties and *Eunotia praerupta* and its varieties occur less frequently.

Assemblage IV was established in a sandy loam covering the organic silt horizon (Fig. 6). More common taxa in this bed include epiphytic halophobic north boreal *Tabellaria fenestrata* (10.4%) and *T. flocculosa*. Rare species are represented by *Hantzschia amphioxys*, *Pinnularia viridis et* vars., *P. brevicostata* var. *semicruciata*, *Neidium iridis*, *Caloneis silicula*, *Diploneis ovalis*, *Navicula dicephala*, *Eunotia praerupta*, *E. parallela*, *Stauroneis anceps*, *Cymbella hybrida*, *C. aspera*, and *Gomphonema longiceps* var. *montana*. This diatom association is typical of small lakes located today on the Siberian tundra (Proshkina-Lavrenko, 1974) and Northern Slope Alaska (Foged, 1968, 1971).

The rare marine diatoms *Thalassiosira gravida* var. *fossilis* and *Paralia sulcata* found in the peat bed (28.6–29.0 masl) suggest that the coastline was nearby (as do the marine diatoms found in assemblage I).

Two abundant assemblages (V–VI) of diatoms were identified in layers of sand with wood remains (29.0–31.3 masl). The diatom flora from these sediments is characterized by high species diversity and abundance which indicate unstable ecological environments (Pushkar and Cherepanova, 1997).

Assemblage V from sediment interval 29.0–30.2 masl contains abundant freshwater cold benthic *Pinnularia hemiptera* (28%) and planktonic *Aulacoseira distans* (17.6%) characteristic of limnic environments (Fig. 6).

Assemblage VI in the upper part of the sediments is characterized by abundant cold-water arcto-boreal benthic *Eunotia triodon* (37.2%), *Navicula bacillum* var. *minor* (14.8%), *Eunotia valida* (8.8%), *E. papilio* (0.8%), *E. praerupta* and its varieties (8.0%) and temperate boreal *Cymbella cuspidata* (7.2%), *C. gracilis* (8.0%), *C. naviculivormis* (15.2%) and *C. perpusilla* (12.0%). This assemblages is also typical of modern small Arctic lakes and swamps (Foged, 1968, 1971; Proshkina-Lavrenko, 1974).

Section Bl 3 is situated stratigraphically below Bl 2 and consists of the upper Qcb and lower Qbs (Fig. 3). The diatom assemblage of the Qcb consists of rare *Paralia sulcata*, *Thalassiosira gravida* and its variety *fossilis*, *Actinocyclus ochotensis* var. *fossilis*, and *Proboscia barboi*. The diatom assemblage from the base of Qbs near its contact with the Qcb is characterized by abundant *Paralia sulcata* (68%) and *Thalassiosira gravida* var. *fossilis* (12.0%). Extinct species are represented by rare *Proboscia barboi*, *Pr. curvirostris*, *Actinocyclus ochotensis* var. *fossilis*,

Thalassiosira nidulus var. *nidulus*, and *Th. jouseae*. The paleoecological structure is formed mainly by arctic and arcto-boreal diatoms (80%). However, the moderately warm species *Coscinodiscus radiatus* and *Cyclotella striata* are also present. These latter two species indicate that the lowermost beds of the Qbs do not reflect a glaciomarine environment.

Sections Blv 1 and Blv 2 are situated immediately north of the 'Elbow', approximately 1.2 km south of section Bl 1 (Figs. 1 and 3). The diatom assemblage of Blv 2 (Qcb) is dominated by north-boreal sublittoral *Paralia sulcata* (40.8%) and *Thalassiosira gravida* var. *fossilis* (6.0%). The paleoecological structure consists of cold-water (82.0%) and warm-water (11.0%) diatom groups. This diatom association is similar to the Bl 1 assemblage.

The Blv 1 assemblage (Qsel) is dominated by freshwater arcto- and north-boreal *Ellerbekia arenaria* var. *teres* (Brun.) Crawford, *Eunotia monodon* and its variety *E. formica*, *Pinnularia interrupta*, and *Navicula bacillum* var. *minor*. This diatom assemblage is directly correlated with the upper part of Qsel diatom association Bl 2 (assemblage VI above), but reflects a deeper facies of a periglacial lake according to limnophilic *Ellerbekia arenaria* var. *teres* and *Pinnularia interrupta*. Biotopes with water depths of about 10 m and a sandy bottom are the ecological optimum for *E. arenaria* var. *teres*.

Section Bl 8 is located about 20 km southeast of Cape Blossom (Figs. 1 and 3). All three stratigraphic units (Qcb, Qbs, Qsel) are observed in this section (Fig. 7). In general, the section is characterized by low diatom abundance due to the coarseness of the deposits. The total number of diatom valves per 1 g dry sediment was less than 0.25×10^6. Only in the uppermost part of the section does abundance increase to 0.68×10^6 diatoms/g. These diatom assemblages do not give a complete picture of the zonal stratigraphy and paleogeographic reconstruction.

Assemblage I from section Bl 8 (2.0–4.5 masl) is dominated by *Paralia sulcata* (7.6%). Others diatoms are rare (1–3%). Among them extinct *Proboscia curvirostris*, *Pr. barboi*, and *Thalassiosira gravida* var. *gravida* are present. The main ecological feature of this assemblage is indicated by moderate and warm diatoms *Actinocyclus curvatulus*, *A. octonarius*, *Actinoptychus senarius*, *Coscinodiscus*

radiatus, *C. asteromphalus*, and *Hyalodiscus obsoletus*. The index species *Proboscia barboi* places this unit within the *Proboscia barboi* Zone, while the 'warm' paleoecological structure strongly suggests that this unit correlates specifically to OIS 11.

Assemblage II (4.5–9.0 masl) is characterized by very rare marine cold-water diatoms *Coscinodiscus marginatus*, *Diploneis smithii*, *Paralia sulcata* and moderate *Actinocyclus curvatulus* and *Coscinodiscus asteromphalus*. The last species is not found in modern biotopes of the Chukchi Sea. This assemblage was found in the lowermost beds of the Qbs unit. The contact between these assemblages shows an unconformity marked by a pebble bed (up to 2 cm thick) indicating the presence of a hiatus between these stratigraphic units. Assemblage II correlates with the *Proboscia barboi* Zone in the lowermost part of the Qbs of section 1 (8.5–9.0 masl). These assemblages with moderate paleoecological structures reflect warm conditions of OIS 11 and do not reflect the cold period through OIS 10. A paleodepth of about 20–30 m is the ecological optimum for a diatom community with *Paralia sulcata* and *Diploneis smithii* dominating (Jousé, 1962; Round, 1970).

Assemblage III (9.0–18.0 masl) unconformably overlies assemblage II. A sudden shift of the paleoecological structure from marine to freshwater indicates the presence of a hiatus. In the lower part of this assemblage (9.0–12.5 masl) the diatom assemblages are dominated by arcto/boreal benthic freshwater *Eunotia triodon*, *E. valida*, and *Pinnularia viridis*. Consistent but rare taxa in this interval include limnophylous planktonic *Aulacosira granulata*, *Tabellaria fenestrata*, *T. flocculosa*, and epiphytic taxa of the genus *Cymbella* which is only found in lacustrine littoral environments. The marine valves *Thalassiosira gravida* var. *fossilis* may be reworked.

A slightly different assemblage was found in interbedded sand and silty sand in the interval of 15.2–18.0 masl. This poorer assemblage includes the same assemblage as the lower part of Qsel unit freshwater diatoms, except *Pinnularia viridis* et vars. and reworked older *Thalassiosira gravida* var. *fossilis* are present. Freshwater diatoms such as *Cymbella aspera*, *Eunotia faba*, *E. fallax*, *Hantzschia amphioxys* var. *capitata* and *Pinnularia microstauron* appear in this bed.
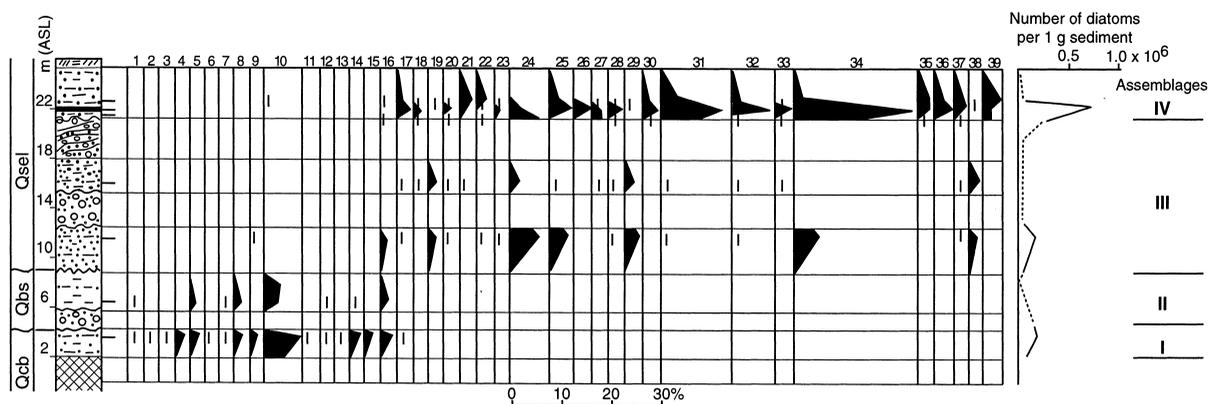
Fig. 7. Diatom diagram of section Bl 8. 1–16 = marine diatoms: 1 = *Actinocyclus curvatulus* Janisch; 2 = *A. ochotensis* var. *ochotensis* Jousé; 3 = *A. octonarius* var. *octonarius* Ehr.; 4 = *Actinoptychus senarius* Ehr.; 5 = *Coscinodiscus marginatus* Ehr.; 6 = *C. radiatus* Ehr.; 7 = *C. asteromphalus* Ehr.; 8 = *Diploneis smithii* (Breb.) Cl.; 9 = *Hyalodiscus obsoletus* Sheshukova; 10 = *Paralia sulcata* (Ehr.) Cl.; 11 = *Stephanopyxis turris* var. *cylindrus* Grun.; 12 = *Proboscia curvirostris* (Jousé) Jordan et Priddle; 13 = *Pr. barboi* (Brun) Jordan et Priddle; 14 = *Rhizosolenia hebetata* (Bail.) Gran; 15 = *Rh. hebetata* var. *hiemalis* (Bail.) Gran; 16 = *Thalassiosira gravida* var. *fossilis* Jousé. 17–39 = freshwater diatoms: 17 = *Aulacoseira granulata* var. *granulata* (Ehr.) Sim.; 18 = *Cymbella aspera* (Ehr.) Cl.; 19 = *C. cuspidata* Kuetz.; 20 = *C. cymbiformis* Ag.? (Kuetz) V.H.; 21 = *Eunotia faba* (Ehr.) Grun. and *E. fallax* A. Cl.; 22 = *E. monodon* Ehr.; 23 = *E. praerupta* Ehr., var. *bidens* (W.Sm.) Grun. and var. *muscicola* Boye; 24 = *E. triodon* Ehr.; 25 = *E. valida* Hust.; 26 = *Fragilaria virescens* Ralfs; 27 = *Hantzschia ampioxys* var. *capitata* O. Müll.; 28 = *Navicula amphibola* Cl.; 29 = *N. bacillum* var. *minor* V.H.; 30 = *N. protracta* Grun.; 31 = *Pinnularia brevicostata* Cl. and var. *semicruciata* A. Cl.; 32 = *P. hemiptera* (Kuetz.) Cl.; 33 = *P. microstauron* (Ehr.) Cl. and var. *brebissonii f. diminuta* Grun.; 34 = *P. viridis* var. *viridis* (Nitzsh.) Ehr., var. *intermedia* Cl. and var. *sudetica* (Hilse) Cl.; 35 = *Stauroneis acuta* W.Sm.; 36 = *S. anceps* Ehr. and *S. phoenicenteron* Ehr.; 37 = *Tabellaria flocculosa* (Roth.) Kuetz. and *T. fenestrata* (Lyngb.) Kuetz.; 38 = *Pinnularia streptoraphe* Cl.; 39 = *Achnanthes kryophila* Boye.

The next assemblage, IV (22.0–25.5 masl), is richer and includes mainly species of the genera *Pinnularia* and *Eunotia*. Swampy ecotopes are the ecological optimum for this community (Proshkina-Lavrenko, 1974; Pushkar, 1979). In an organic-rich interlayer, the diatom flora is represented by abundant cold-water benthic *Pinnularia brevicostata* and *P. viridis*. The cryophillic *Achnanthes kryophila* appears at the base of this interval. This assemblage becomes less common, and taxa disappear toward the top of the silty bed (Fig. 7). The paleoecological structure of these associations correspond to the littoral zone of a swampy, shallow lake. The paleoclimatic conditions were colder than modern, but with a clear short summer period of diatom reproduction under surface water temperatures of about 7–10ºC as was shown for similar assemblages from a recent freshwater basin of Arctic Siberia (Proshkina-Lavrenko, 1974; Komarenko and Vassilyeva, 1975). The presence of brackish-water *Navicula protracta* indicates the proximity of the marine shoreline.

Section BI 4 and 5 are both located 4 km north of the 'Elbow' and consist of coarse and medium to fine, well-sorted sand with thin interbeds of silt up to 2–3 cm thick and are interpreted to be part of the Qsel member. Diatom flora found in these sections are very rare, probably because these units formed under a higher-energy setting. The mixed complex consisting of both typical halophobous freshwater and marine diatoms argues for a prodeltaic provenance. The marine diatoms are represented by extinct *Thalassiosira gravida* var. *fossilis* and extant *Coscinodiscus marginatus*, *Thalassiosira gravida* var. *gravida* and *Th. eccentrica*. The freshwater diatoms *Ellerbeckia arenaria*, *Pinnularia viridis*, *P. borealis*, and *Eunotia triodon* are also present. It is very difficult to define the age of these units based on these assemblages. The age based on *Thalassiosira gravida* var. *fossilis* is not younger than middle Pleistocene. We consider these deposits as facies equivalents of lacustrine sediments of the Qsel of sections 2 and 8.

6. Paleoenvironmental interpretations

6.1. Cape Blossom Formation

The diatom assemblages in the Qcb correlate to the middle of the *Proboscia barboi* Zone (Fig. 4) and the presence of warm-water diatoms indicates that the Qcb was deposited during the marine high sea level associated with the warm OIS 11 transgression. According to the T_d values of the Qcb diatom assemblages (Fig. 5) the average annual temperature of KS surface waters during deposition of the Qcb was 6º–7ºC higher than at present, based on comparison of modern diatom thanatocoenoses from the northwest Pacific which has an annual average temperature of about 18º–16ºC (Jousé, 1962; Proshkina-Lavrenko, 1974; Sancetta, 1982a). High paleotemperature estimates (T_d up to 19.7%) were likely caused by both increased surface water temperature and the penetration of warm currents from the northeastern Pacific through the Bering Strait into the Chukchi Sea. Some of the moderately warm-water diatom species (e.g., *Coscinodiscus asteromphalus*) were also reported by Ivanov (1986) from the middle Pleistocene (OIS 11) Yanrakinot Formation from eastern Chukotka.

The high abundance of *Paralia sulcata* in the Qcb diatom assemblages indicates that this assemblage formed in about 20 m water depth. The Qcb deposits on the Baldwin Peninsula currently extend up to an altitude of 15 masl. In light of this and considering the relatively stable tectonic position of Kotzebue Sound, it is very difficult to conclude that eustatic sea level rose more than 35 masl during the OIS 11 transgression. However, if the suggestion that the Anvilian deposits have undergone no more that 13 m of tectonic uplift (Kaufman et al., 1991) is correct, and extrapolating this uplift value to Baldwin Peninsula, we can estimate the original, non-uplifted upper boundary of the Qcb to 2 masl. In this case, we can conclude that the eustatic sea level rose up to 22–25 masl during the middle Pleistocene OIS 11 transgression. This high stand estimate correlates well with Hopkins' estimate of sea-level rise (Hopkins, 1973) during the Einahnuhtan transgression of the middle Pleistocene. These results are also comparable to results we have got by diatom analysis of the 40 m terrace on the tectonically active Kunashiri Island (Kurile Islands) (V.S. Pushkar, unpublished

data) which indicate that the eustatic sea level rose 20–25 masl during the middle-late *Proboscia barboi* time (OIS 11).

Other described diatom assemblages from the middle part of the *Proboscia barboi* Zone which are correlative to the OIS 11 transgression include the middle Pleistocene deposits of northern Siberia (Polyakova, 1989, 1991; Losseva, 1992), Subarctic Pacific (Sancetta and Silvestri, 1986; Pushkar et al., 1987; Barron and Gladenkov, 1995), Kamtschatka (Basilyan et al., 1993; Gladenkov, 1994), and the Okhotsk Shelf (Pushkar and Cherepanova, 1996).

6.2. Baldwin Silt and Selawik members of the Hotham Inlet Formation

The moderately warm diatom assemblage at the base of Qbs, including species such as *Coscinodiscus radiatus*, *C. asteromphalus*, and *Thalassiosira oestrupii* (Fig. 5), indicate that the lower 2 m of these sediments formed under transgressive conditions during OIS 11, similar to conditions during deposition of the Qcb. The boundary between marine and glaciomarine units must therefore be placed in the lower part of the Qbs rather than at the Qcb/Qbs lithologic contact. The diatom complexes of the middle and upper parts of the Qbs directly indicate that the connection between watermasses of the Pacific and Arctic oceans terminated and colder conditions were initiated. A similar situation was described by Verkhovskaya (1986) for the eastern Siberian glacial deposits. The cold glaciomarine genesis of the middle and upper Qbs is supported by the following points. Firstly, the presence of marine cryophilic diatoms *Thalassiosira cryophila*, *Th. hyalina*, *Bacterosira fragilis*, and probably *Thalassiosira nordenskoeldii* (Jousé, 1962; Sancetta, 1982a) are evidence of a glaciomarine origin. Secondly, the very rare distribution of the diatom valves in the glaciomarine sediment (less than 0.2×10^6 diatoms/g) and the presence of freshwater species are taken to indicate high sedimentation rates caused by influxes of glacial meltwater and sediments into KS. The freshwater association is represented by diatoms with different ecological habitats (rivers, springs, swamps, and lakes) and does not reflect specific ecological niches but rather indicates the redeposition of these diatoms. Thirdly, moderate marine diatoms were not found in this unit.

Sea-level position during Qbs deposition is difficult to constrain. The basal lag at the Qcb–Qbs contact is interpreted as a type III (omission-based) or type IV (erosion-based) condensed sequence of Kidwell (1986, 1989), both of which result from erosion and cessation of sedimentation during a marine transgression. In the middle and upper Qbs, the cold T_d and cryophilic diatom assemblages indicate cooler conditions and initiation of glaciomarine deposition in KS while the shelf remained flooded, during and immediately following OIS 11. Glaciomarine sedimentation must have started while the shelf remained flooded during OIS 11 when sea level was nearly as high as it is today because a relatively small drop in eustatic sea level ($\approx$40 m) would have caused the shoreline to regress over 200 km to the northwest. However, it is difficult to specify how over 20 m of glaciomarine Qbs accumulated on the shallow shelf where water depth was about 20 m according to the ecological optimum of the *Paralia sulcata– Diploneis smithii* association. Advancing ice from the Noatak, Kobuk, and Selawik river valleys may have isostatically depressed the Kotzebue Basin, creating an embayment to the deeper Chukchi Sea and thus maintaining the glaciomarine environment into OIS 10. But in order to maintain marine conditions in KS, the rate of glacioisostatic submergence must have outpaced the rate of global sea-level regression. Glaciomarine deposition must have started in KS just after the peak transgression associated with OIS 11 and was likely subsequently maintained by the glacioisostatic depression. Diatom assemblages indicate that the middle and upper Qbs formed during OIS 10, with the bulk of the Qbs and Qsel formed during periglacial conditions associated with retreat of the glaciers.

The gradational contact of the Qbs with the Qsel glacial outwash deposits indicate that Qsel deposition initiated as episodic pulses against the background pelagic sedimentation of the Qbs. The diatom cliseries of sites Bl 2 and Bl 8 clearly indicate that climate was not stable during the deposition of Qsel. Ice-wedge pseudomorphs observed in the upper Qsel attest to cold conditions and aggrading permafrost during progradation of the glacial outwash plain, suggesting that as glacial outwash plains developed in the KS region, sea level had regressed off the KS shelf.

7. Paleoclimatic implications

Because it is apparent that eustatic sea level remained high during the transition from non-glacial to glaciomarine sedimentation, glaciers must have advanced over 200 km from the Brooks Range to KS during the global interglacial conditions of OIS 11. Glacier growth in this region may have been facilitated by abundant moisture provided by penetration of warm Pacific surface waters into the Bering and Chukchi seas, and the absence of long periods of seasonal ice cover. Verkhovskaya proposed similar arguments for the middle Pleistocene glacial events of Chukotka (Verkhovskaya, 1986; Verkhovskaya and Kundyshev, 1987). The combined conditions of warm oceans and cold continental interiors have also been found to favor expansion of the Laurentide Ice Sheet in the eastern Canadian Arctic (Andrews, 1988; Lemmen and England, 1992; Miller and de Vernal, 1992). These authors demonstrate that High Arctic ice sheet expansion during the last 150 ka was favored by warm oceanic surface waters during winter, strong meridional oceanic and atmospheric circulation, and low summer air temperatures. Ice sheet growth at high northern latitudes (65–80ºN) apparently was initiated during climatic conditions similar to modern (Miller and de Vernal, 1992). In latest Pleistocene time, snow accumulation in the Greenland ice sheet was greatest during warm intervals (Alley et al., 1993). The record of middle Pleistocene glacial inception in northwestern Alaska is consistent with these observations of late Pleistocene ice growth. The biostratigraphic record at Baldwin Peninsula provides further evidence that high-latitude ice growth is favored by increased moisture supply during warm climatic intervals and hampered by arid conditions during full glacial intervals. This last concept is very important, because some modelers of ice sheets erroneously believe that they can grow large ice sheets in the Arctic simply by lowering mean annual temperature without consideration of moisture availability (e.g., Hughes and Hughes, 1994).

8. Conclusions

(1) The Cape Blossom Formation, and Baldwin Silt and Selawik Gravel members of the Hotham

Inlet Formation correlate to the *Proboscia barboi* diatom zone (0.52–0.28 Ma) of the North Pacific. Our precise age estimates were obtained through analysis of the ecologic succession of diatom assemblages due to environmental and climatic changes. The Cape Blossom Formation and lowermost Baldwin Silt sediments formed during the warm, high-sea-level event associated with OIS 11.

(2) Glaciers advanced from the Brooks Range near the end of OIS 11, with glaciomarine sedimentation occurring in Kotzebue Sound before sea level regressed during OIS 10. The middle and upper Baldwin Silt and Selawik Gravel members formed during OIS 10. Local sea level dropped before glaciers reached Kotzebue Sound, as eustatic sea-level regression outpaced glacioisostatic depression.

(3) Extensive middle Pleistocene glacier growth in northwestern Alaska during warm global interglacial conditions was likely facilitated by abundant moisture provided by warm Pacific surface waters flooding the Bering and Chukchi shelves. Retreat of these glaciers began after the warm Pacific water supply was terminated. Glacial expansions in the Arctic may be out-of-phase with mid-latitude ice sheet expansion due to a combination of moisture availability associated with high sea level and earlier continental cooling at higher latitudes.

(4) Extension of the Plio–Pleistocene diatom biostratigraphic zonation scheme into the Bering/Chukchi seas will provide an improved means of correlating extensive transgressive marine and glaciomarine deposits in western Beringia (eastern Russia and Chukotka) with the more thoroughly studied deposits in western Alaska.

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